

# Anatomy of Higgs mass in Supersymmetric Inverse Seesaw Models

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## Abstract

We compute the one loop corrections to the CP even Higgs mass matrix in the supersymmetric inverse seesaw model to single out the different cases where the radiative corrections from the neutrino sector could become important. It is found that there could be a significant enhancement in the Higgs mass even for Dirac neutrino masses of  $\mathcal{O}(30)$  GeV if the left-handed sneutrino soft mass is comparable or larger than the right-handed neutrino mass. In the case where right-handed neutrino masses are significantly larger than the supersymmetry breaking scale, the corrections can utmost account to an upward shift of 3 GeV. For very heavy multi TeV sneutrinos, the corrections replicate the stop corrections at 1-loop. We further show that general gauge mediation with inverse seesaw model naturally accommodates a 125 GeV Higgs with TeV scale stops.

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## I. INTRODUCTION

The discovery of the Higgs boson [1–3] of the standard model has put severe constraints on its supersymmetric extensions. In particular, for light stops masses (below 1 TeV), maximal stop mixing is required to generate a Higgs mass  $\sim 125$  GeV [4–10]. Many supersymmetry breaking models have already been strongly constrained by this requirement [11–19].

On the other hand, neutrino masses constitute one of the strongest signatures of physics beyond standard model. It is imperative that any supersymmetric extension of the standard model should also contain an explanation for non-zero neutrino masses. Among many ideas to generate tiny neutrino masses, the inverse seesaw model [20] is interesting as it is applicable at the weak scale with neutrino Yukawa coupling of order one, and thus testable at colliders like LHC.

In the present work, we revisit the consequences of the inverse seesaw model for the lightest CP even Higgs boson mass [21, 22]. We find parameter regions in which the one-loop corrections to the light Higgs mass can be very significant, leading to an increase of  $\mathcal{O}(10)$  GeV, for the neutrino Yukawa coupling larger than about 0.2. This is in the line of observations of Refs. [23, 24] which explored the role of extra vector like matter at TeV scale in increasing the light Higgs mass. We then apply these corrections to phenomenological minimal supersymmetric standard models (PMSSM) and general gauge mediated supersymmetry breaking models (GMSB) where the Higgs mass can become 125 GeV for supersymmetry breaking scale around TeV.

The paper is organized as follows. In the next section, we present one loop corrections to the Higgs mass and study the various parameter regimes. In the section 3, we work out two numerical examples in (1) PMSSM (2) General gauge mediated supersymmetric inverse seesaw model. We conclude in the section 4. Appendix A contains the main formulae, whereas appendices B and C contain RGE equations and some ancillary formulae.

## II. ONE LOOP CORRECTIONS TO THE HIGGS MASS IN MSSM

The inverse seesaw model is characterized by a small lepton number violating mass, unlike the Type-I seesaw, the right-handed neutrinos can be as light as TeV or even below, with their Yukawa couplings of order one. This is achieved by having an additional singlet field, which we denote by  $S$ . The superpotential for this model is given as

$$W_{\text{SISM}} = W_{\text{MSSM}} + Y_N L H_u N^c + M_R N^c S + \mu_S S S \quad (1)$$

where  $W_{MSSM}$  stands for the standard MSSM superpotential,

$$W_{MSSM} = Y_U Q U^c H_u + Y_D Q D^c H_d + Y_E L E^c H_d + \mu H_u H_d \quad (2)$$

and  $N^c$  and  $S$  are singlet fields carrying lepton number  $+1, -1$  respectively.

We consider one right-handed neutrino and one singlet  $S$  field in the discussion. It can be easily generalized to the case of two/three generations. The mechanism of how neutrino gets mass is well documented in the literature. We revisit it here briefly. In the basis,  $\{\nu_L, N^c, S\}$ , the mass matrix,  $M_\nu$ , for the neutral leptons is given by

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D & 0 & M_R \\ 0 & M_R & \mu_S \end{pmatrix} \quad (3)$$

Where  $m_D = Y_N \langle H_u \rangle$ . The eigenvalues are given as

$$\begin{aligned} m_{\nu_1} &\approx \frac{m_D^2 \mu_S}{M_R^2} \\ m_{\nu_2} &\approx -\left( \frac{m_D^2}{2 M_R} + M_R \right) \\ m_{\nu_3} &\approx \left( \frac{m_D^2}{2 M_R} + M_R \right) \end{aligned}$$

$m_{\nu_1}$  is the lightest neutrino eigenvalue proportional to the lepton number violating parameter  $\mu_S$ , the other two eigenvalues are almost degenerate  $\sim M_R$ .

Since the inverse seesaw model is typically a low scale model, unlike the traditional seesaw mechanisms, one wonders if they can give large enough contribution to the light CP-even Higgs boson mass. This is more important to explore in the regions where  $m_D$  can be relatively large  $\gtrsim 10$  GeV. It should be noted that the range in  $m_D \simeq (0.2 - 0.3)v$  for has been explored by collider searches [25, 26]. There are constraints, however, on the size of  $m_D$  for a given value of  $M_R$  from electroweak precision tests [27]:

$$m_D \lesssim 0.05 M_R \quad (4)$$

This constraint is strictly for the electron and muon generations. For the third generation, it is slightly weaker, at the level of 0.07. This requires  $M_R \simeq 3$  TeV for  $m_D$  close to the top quark mass. To compute the corrections to the light Higgs mass from the neutrino sector, we use the one loop effective potential methods of Coleman-Weinberg [28]. The methods have been used to derive the well-known one-loop corrections from the top-stop sector [29, 30] and we extend them to the neutrino sector in the inverse seesaw model.

The scalar potential in this model consists of

$$V_S = V_F + V_D + V_{\text{soft}} \quad (5)$$

where

$$\begin{aligned} V_F &= |Y_e E H_d + Y_N H_u N|^2 + |Y_u Q u^c + \mu H_d + Y_N L N^c|^2 + |Y_N L H_u + M_R S|^2 + |M_R N^c + \mu_S S|^2 + \dots \\ V_D &= \frac{1}{8}(g^2 + g'^2)(|H_u|^2 - |H_d|^2) \\ V_{\text{soft}} &= A_N L H_u N^c + B_M N S + B_{\mu_S} S S + H.c + \dots \end{aligned} \quad (6)$$

In the basis,  $\{\tilde{\nu}_L, \tilde{N}^c, \tilde{S}\}$ , the mass matrix,  $\mathcal{M}_{\tilde{\nu}}^2$ , for the sneutrinos is given by

$$\mathcal{M}_{\tilde{\nu}}^2 = \begin{pmatrix} m_L^2 + D_L + m_D^2 & m_D(A_N - \mu \cot \beta) & M_R m_D \\ * & m_D^2 + m_N^2 + M_R^2 & B_M + M_R \mu_S \\ * & * & M_R^2 + \mu_S^2 + m_S^2 \end{pmatrix}. \quad (7)$$

In the above matrix, elements with \* correspond to symmetric entries of the mass matrix. The eigenvalues of the above mass matrix can be easily derived in the limit  $\mu_S \ll m_D \ll M_R$ , as required by the inverse seesaw mechanism and the electroweak precision tests. In the leading order of  $m_D M_R/d_2, m_D X_N/d_1 \ll 1$ , they are given as

$$\begin{aligned} m_{\tilde{\nu}_1}^2 &\approx m_L^2 + m_D^2 \left(1 + \frac{M_R^2}{d_2} + \frac{X_N^2}{d_1}\right) \\ m_{\tilde{\nu}_2}^2 &\approx m_N^2 + M_R^2 + m_D^2 \left(1 - \frac{X_N^2}{d_1}\right) \\ m_{\tilde{\nu}_3}^2 &\approx m_S^2 + M_R^2 - \frac{M_R^2 m_D^2}{d_2} \end{aligned}$$

where

$$\begin{aligned} d_1 &= m_L^2 - m_N^2 - M_R^2 \\ d_2 &= m_L^2 - m_S^2 - M_R^2. \end{aligned}$$

One-loop corrections for the Higgs mass matrix will be derived from the one-loop effective scalar potential given by the standard form:

$$V_{1-loop}(q^2) = \frac{1}{64\pi^2} \mathcal{S}Tr \mathcal{M}^4(h) \text{Log} \left( \frac{\mathcal{M}^2(h)}{q^2} - \frac{3}{2} \right). \quad (8)$$

In the basis  $\Phi^T = (Re\{H_d^0\}, Re\{H_u^0\})$ , the corrections to the CP even Higgs mass are given as

$$\mathcal{M}^2 = \mathcal{M}_0^2 + \Delta \mathcal{M}_t^2 + \Delta \mathcal{M}_\nu^2$$

where  $\mathcal{M}_0^2$  stands for the tree level mass matrix,  $\Delta\mathcal{M}_t^2$  and  $\Delta\mathcal{M}_\nu^2$  are contributions from the top/stop sector and the neutrino/sneutrino sectors respectively. The full mass matrix has the form:

$$\begin{aligned}\mathcal{M}_{11}^2 &= M_Z^2 \cos \beta^2 + m_A^2 \sin \beta^2 + \Delta\mathcal{M}_{t_{11}}^2 + \Delta\mathcal{M}_{\nu_{11}}^2 \\ \mathcal{M}_{12}^2 &= -(M_Z^2 + m_A^2) \cos \beta \sin \beta + \Delta\mathcal{M}_{t_{12}}^2 + \Delta\mathcal{M}_{\nu_{12}}^2 \\ \mathcal{M}_{22}^2 &= M_Z^2 \sin \beta^2 + m_A^2 \cos \beta^2 + \Delta\mathcal{M}_{t_{22}}^2 + \Delta\mathcal{M}_{\nu_{22}}^2\end{aligned}$$

where for the sake of completeness, we present the well known top/stop contributions [29, 30] :

$$\begin{aligned}\Delta\mathcal{M}_{t_{11}}^2 &= \frac{3g_2^2 m_t^4}{16\pi^2 M_W^2 \sin \beta^2} \left( \frac{\mu X_t}{m_{t_1}^2 - m_{t_2}^2} \right)^2 g(m_{t_1}^2, m_{t_2}^2) \\ \Delta\mathcal{M}_{t_{12}}^2 &= \frac{3g_2^2 m_t^4}{16\pi^2 M_W^2 \sin \beta^2} \left( \frac{\mu X_t}{m_{t_1}^2 - m_{t_2}^2} \right) \log \left( \frac{m_{t_1}^2}{m_{t_2}^2} \right) - \frac{A_t}{\mu} \Delta\mathcal{M}_{t_{11}}^2 \\ \Delta\mathcal{M}_{t_{22}}^2 &= \frac{3g_2^2 m_t^4}{16\pi^2 M_W^2 \sin \beta^2} \left( 2 \log \frac{Q^2}{m_t^2} + \frac{2A_t X_t}{m_{t_1}^2 - m_{t_2}^2} \log \left( \frac{m_{t_1}^2}{m_{t_2}^2} \right) \right) + \left( \frac{A_t}{\mu} \right)^2 \Delta\mathcal{M}_{t_{11}}^2\end{aligned}\quad (9)$$

In the following we write down the contribution from the neutrino sector in a compact notation as follows:

$$\begin{aligned}\Delta\mathcal{M}_{\nu_{11}}^2 &= 2k \left( \tilde{L}_1 \tilde{B}_{11}^2 + \tilde{L}_2 \tilde{B}_{21}^2 + \tilde{L}_3 \tilde{B}_{31}^2 + m_{\tilde{\nu}_1}^2 \tilde{A}_{111}(\tilde{L}_1 - 1) + m_{\tilde{\nu}_2}^2 \tilde{A}_{211}(\tilde{L}_2 - 1) + m_{\tilde{\nu}_3}^2 \tilde{A}_{311}(\tilde{L}_3 - 1) \right) \\ \Delta\mathcal{M}_{\nu_{22}}^2 &= 2k \left( \tilde{L}_1 \tilde{B}_{12}^2 + \tilde{L}_2 \tilde{B}_{22}^2 + \tilde{L}_3 \tilde{B}_{32}^2 + m_{\tilde{\nu}_1}^2 \tilde{A}_{122}(\tilde{L}_1 - 1) + m_{\tilde{\nu}_2}^2 \tilde{A}_{222}(\tilde{L}_2 - 1) + m_{\tilde{\nu}_3}^2 \tilde{A}_{322}(\tilde{L}_3 - 1) \right) \\ &\quad - 4k \left( L_2 B_{22}^2 + L_3 B_{32}^2 + m_{\nu_2}^2 A_{222}(L_2 - 1) + m_{\nu_3}^2 A_{322}(L_3 - 1) \right) \\ \Delta\mathcal{M}_{\nu_{12}}^2 &= 2k \left( \tilde{L}_1 \tilde{B}_{12} \tilde{B}_{11} + \tilde{L}_2 \tilde{B}_{22} \tilde{B}_{21} + \tilde{L}_3 \tilde{B}_{32} \tilde{B}_{31} + m_{\tilde{\nu}_1}^2 \tilde{A}_{112}(\tilde{L}_1 - 1) + m_{\tilde{\nu}_2}^2 \tilde{A}_{212}(\tilde{L}_2 - 1) \right. \\ &\quad \left. + m_{\tilde{\nu}_3}^2 \tilde{A}_{312}(\tilde{L}_3 - 1) \right)\end{aligned}\quad (10)$$

In the above,

$$\begin{aligned}g(A, B) &= 2 - \frac{(A+B)}{(A-B)} \log \frac{A}{B}; \quad k = \frac{2}{32\pi^2} \\ \tilde{L}_i &= \text{Log} \left( \frac{m_{\tilde{\nu}_i}^2}{Q^2} \right); \quad L_i = \text{Log} \left( \frac{m_{\nu_i}^2}{Q^2} \right) \\ X_t &= A_t - \mu \cot \beta\end{aligned}$$

and  $B_{ij}$  and  $A_{ijk}$ 's are given in the Appendix. While the above formulae are written for a single generation of right handed and singlet neutrinos, they can be easily generalized to three generations of right-handed and singlet neutrinos. The neutrino contributions to the light Higgs mass, though similar to those from the top/stop sector, have a couple of distinct features: (a) there is no

colour factor associated with the neutrino contributions, so they typically lower than the top/stop contributions by a factor three, (b) The fermionic contributions, from the right-handed neutrinos can be significant, reducing the total contribution to the Higgs mass. This is highly dependent on the hierarchies between the relevant parameters: the soft masses and the right handed neutrino masses. To understand the overall relevance of these contributions, we will consider a few interesting cases below. Note that in our numerical analysis, we restrict  $m_D M_R/d_2, m_D X_N/d_1$  to be less than 0.1.

1. *case-1* :  $M_R \approx m_L$

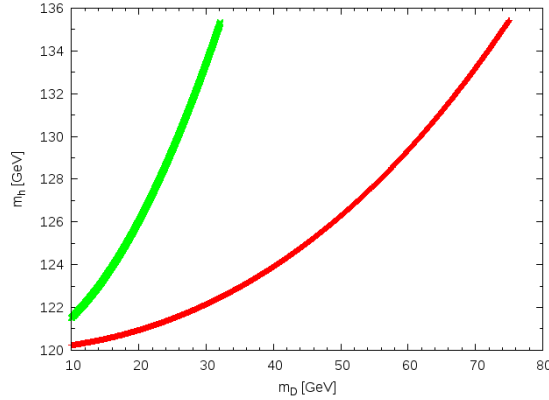


FIG. 1: The lightest CP even Higgs boson mass as a function of  $m_D$  for  $A_N = 0$  (red) and  $A_N = -1000$  GeV (green). In this plot other parameter are fixed as  $M_R = m_L = 1500$  GeV,  $m_N = 1000$  GeV and  $m_S = 800$  GeV. The stop mass parameters are fixed such that  $m_h = 120$  GeV without the neutrino corrections.

In this case <sup>1</sup>, we choose the right-handed neutrino mass scale close to the (left-handed) slepton masses. To satisfy the electroweak precision tests,  $m_D$  should be typically smaller than  $M_R$  by a factor 20. Neutrino masses can be adjusted by choosing a sufficiently small  $\mu_S$ . In Fig. 1 we plot the light Higgs mass as a function of  $m_D$  for two values of  $A_N = 0$  (Red) and  $A_N = -1000$  GeV (Green). The stop contributions are chosen such that the lightest CP even Higgs mass,  $m_h = 120$  GeV and rest of the contribution comes solely from the neutrino sector. As it can be seen from the left panel, the Higgs mass has a significant increase from 120 GeV and the increase is possible even for  $m_D$  values as small as 20 GeV <sup>2</sup> as long as slepton mass  $m_L$  is relatively heavy  $\gtrsim 1$ TeV in the same range of  $M_R$ . The rest of the slepton masses appearing in the 1-loop formula are

<sup>1</sup> see Appendix-C, for approximate formulae for sneutrino eigenvalues

<sup>2</sup>  $m_D$  values quoted here are at the  $M_{SUSY}$  scale which has been fixed at 1 TeV.

chosen to be  $m_N = 1000$  GeV and  $m_S = 800$  GeV. As expected increasing  $A_N$  increases the higgs mass, but the effect varies with increasing  $m_D$ . It should be noted that perturbative constraints exist on the neutrino Yukawa couplings  $y_N = m_D/v_u$ . Requiring  $y_N$  to be perturbative all the way up to the GUT scale, puts a constraint on  $y_N \leq 0.75$  [22]. While we have considered  $M_R \approx m_L$  in the present example, this is not strictly necessary. For example, instead of  $m_L$  in the above case, one can have a similar enhancement in the case  $M_R \approx m_N$ , while  $m_L$  being significantly lighter.  $M_R \approx m_S$  does not lead to significant enhancement because that  $S$  does not couple to the Higgs field,  $H_u$ . In Fig. 2,  $m_L$ ,  $m_D$  and  $A_N$  are fixed to be 1500 GeV, 75 GeV and 0 respectively. And

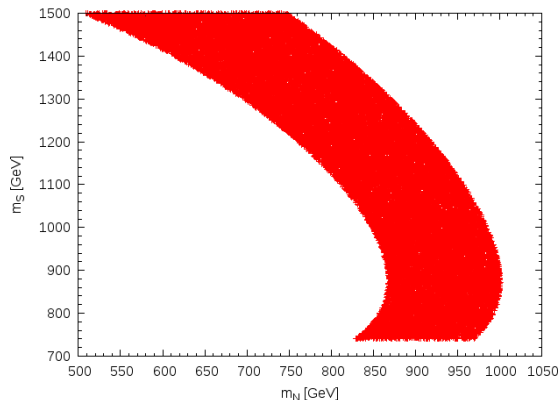


FIG. 2: The red band corresponds to Higgs mass of range [124-126] GeV in the plane of  $m_S$  and  $m_N$ . The rest of the parameters are chosen as  $m_L = M_R = 1500$  GeV,  $m_D = 75$  GeV and  $A_N = 0$ . The stop mass parameters are fixed such that  $m_h = 120$  GeV without the neutrino corrections.

the parameter space in  $m_N$  and  $m_S$  plane is plotted with a restriction that Higgs mass should be in the range [124-126] GeV. Evidently there is wide range of parameter space available which can give Higgs mass of 125 GeV.

## 2. case-2: $M_R \gg m_L$

We now consider the case where  $M_R$  is the largest mass scale in the theory. This limit has been earlier considered in Ref.[22]. In this case, the enhancement in the light Higgs mass is much smaller and restricted to a few GeV. This is because the neutrino 1-loop correction, which is negative, significantly suppresses the total contribution from the neutrino sector. This is illustrated in Fig. 3 where we have plotted  $m_h$  as a function of  $A_N$  (left panel) and  $m_D$  (right panel). The slepton masses are fixed as  $m_L = 500$  GeV,  $m_N = 300$  GeV and  $m_S = 200$  GeV. The right-handed neutrino mass is taken to be 5 TeV. As can be seen from the plots, the enhancement is not significant in this

case. This holds even with the variation in  $A_N$  (left panel) or  $m_D$  (right panel). The maximum enhancement achieved here is about two and half GeV.

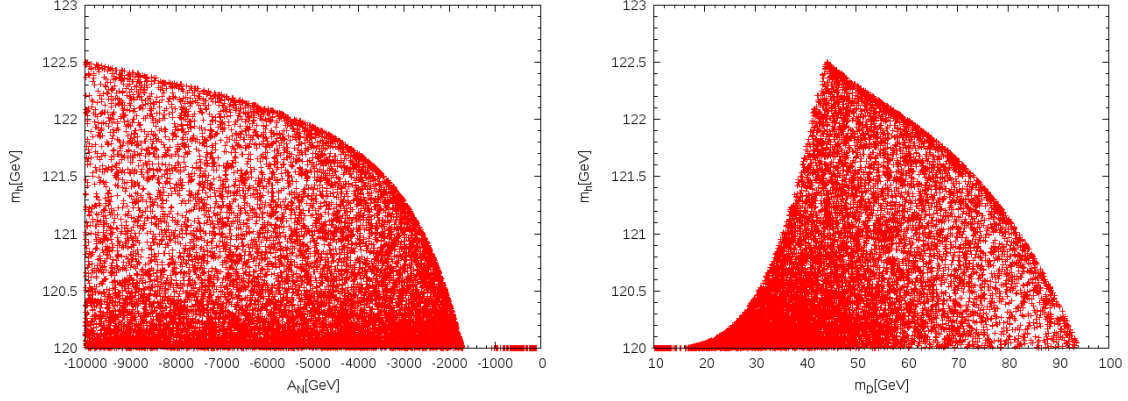


FIG. 3: The lightest CP even neutral Higgs boson is plotted for  $M_R = 5$  TeV with respect to  $A_N$  (left panel) and  $m_D$  (right panel). The rest of the parameters are chosen to be  $m_L = 500$  GeV,  $m_N = 300$  GeV, and  $m_S = 200$  GeV. The stop parameters are taken such that  $m_h = 120$  GeV.

### 3. case-3: $m_L = m_N = m_S \gg M_R$

This case replicates the stop corrections. All the sneutrino eigenvalues are much larger than the neutrino ones and thus dominating over the negative contributions. However, it turns out that the required sneutrino mass scale is in TeV range ( around 2 TeV range for a 500 GeV  $M_R$ ). This range is suited for semi-split and split scenarios. This is depicted in the Fig. 4.

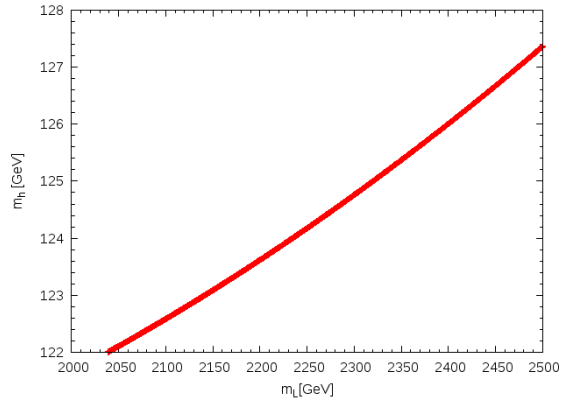


FIG. 4:  $m_h$  is plotted versus  $m_L$  keeping  $M_R = 500$  GeV and  $A_N = 0$ . The stop parameters are taken such that  $m_h = 120$  GeV.



4. case-4:  $M_R = m_{SUSY}$

We now consider the case where  $M_R = M_{SUSY}$ , where  $M_{SUSY} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ . Fixing the stop parameters such that  $m_h = 120$  GeV fixes,  $M_R \approx M_{SUSY} \approx 1$  TeV.  $m_N, m_L$  and  $m_S$  are considered as free parameters. The parameter space  $m_L$  and  $m_N$  which accommodates, Higgs mass in the range 124–126 GeV for different values of  $m_S$  with  $A_N = 0$  and  $A_N = -1$  TeV is shown in Fig. 5.<sup>3</sup>

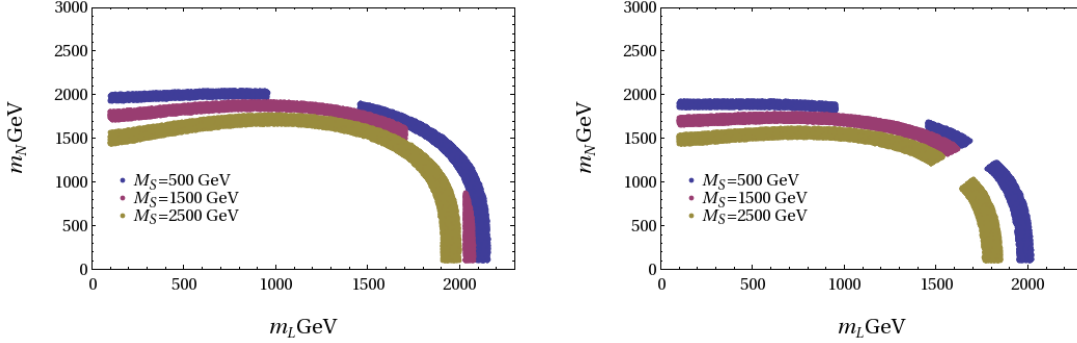


FIG. 5:  $m_L$  is plotted against  $m_N$  with different values of  $m_S$ , for a Higgs mass of 124-126 GeV. The rest of the parameters are chosen to be  $A_N = 0$  (-1 TeV) and  $m_D = 50$  GeV for the left (right) panel. The stop parameters are taken such that  $m_h = 120$  GeV

### III. APPLICATIONS TO PMSSM AND GMSB

In the present section, we present two numerical examples as an application to the above calculation.

#### A. PMSSM and Inverse Seesaw

The phenomenological MSSM is low energy parameterisation of the supersymmetry breaking soft terms in terms of 19-22 parameters (See for example, [31]). To study the inverse seesaw model in the PMSSM setting the following additional parameters  $m_N, m_S, A_N$  are to be included. Together with the existing parameters, the nine parameters which completely fix the low energy neutral CP even Higgs mass matrix and their ranges are given as:  $m_Q, m_U, m_L, m_N, m_S \in [100, 3000]$  GeV;  $A_t, \mu \in [-1500, 1500]$  GeV;  $Y_N \in [0.1, 1]$ .

<sup>3</sup> Points which contribute to poles in sneutrino eigenvalues are removed and are responsible for discontinuity in the plots

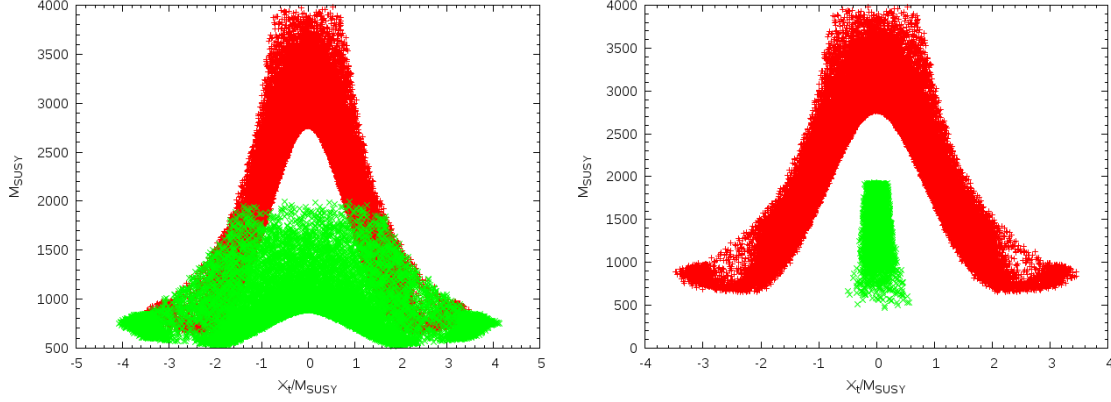


FIG. 6: For a fixed value of  $M_R = 1000$  (2500) GeV in the left (right) panel,  $M_{SUSY}$  is plotted against  $X_t/M_{SUSY}$ . Green (red) points are with (without) neutrino contribution.

In Fig. 6, we have plotted the regions of Higgs mass within the range [123,128] GeV in the plane of  $M_{SUSY}$  and  $X_t/M_{SUSY}$ . In the left (right) panel right-handed neutrino mass is chosen to be 1 (2) TeV. The  $\tan\beta$  is fixed to be 10. The red points are the ones without neutrino/sneutrino contributions and the green points are the ones where neutrino/sneutrino contributions are added. As we can clearly see from the figure, even if  $m_{SUSY}$  is below 1 TeV, there is enough contribution from the neutrino sector to a 125 GeV Higgs mass

As right-handed neutrino mass  $M_R$  increases, we get closer to the case-2 discussed in the previous section where larger right-handed neutrino masses make the contribution of right-handed neutrinos to Higgs mass negative, and thus reducing the Higgs mass. This effect is seen in the right panel of Fig. 6.

## B. GMSB and Inverse Seesaw

Minimal gauge mediation models have been strongly constrained by the recent discovery of the Higgs mass of 125 GeV [5]. This is because the stop mixing parameter  $X_t$  is predicted to be very small in these models. The  $X_t$  can be made large through renormalisation group corrections, but this would require gluino masses to be greater than 8 TeV. Thus, the only way these models can accommodate a light CP even neutral higgs boson with a mass around 125 GeV is by increasing the masses of the stops beyond 4 TeV. This range for the stop masses is far beyond the LHC reach. One can then consider modification by including either messenger-matter interactions, new fields or new interactions to achieve the Higgs mass within the required ball park. The feature of small  $X_t$  also persists in general gauge mediation which is an umbrella of all possible gauge mediations

both in the perturbative and non-perturbative regime. A recent analysis of the Higgs mass in general gauge mediation is presented in Ref. [32].

Incorporating the inverse seesaw model in general gauge mediation could generate the Higgs mass in the right ball park, due to the additional corrections induced by the neutrinos. We study this possibility in the present subsection. The set up of general gauge mediation we consider is specified by the following boundary conditions at the messenger scale:

$$\begin{aligned}
M_i(X) &\approx \frac{\Lambda}{16\pi^2} \sum_i (g_i^2(X)) \\
m_Q^2 &\approx \frac{2\Lambda^2}{(16\pi^2)^2} \sum_i (g_i^4(X) C_i(Q)) \\
m_U^2 &\approx \frac{2\Lambda^2}{(16\pi^2)^2} \sum_i (g_i^4(X) C_i(U)) \\
m_L^2 &\approx \frac{2\Lambda_L^2}{(16\pi^2)^2} \sum_i (g_i^4(X) C_i(L)) \\
m_e^2 &\approx \frac{2\Lambda_L^2}{(16\pi^2)^2} \sum_i (g_i^4(X) C_i(L)) \\
m_{\tilde{S}}^2 &= 0 \\
m_N^2 &= 0
\end{aligned}$$

Where  $C_i(f)$  is the quadratic casimir of the field  $f$  and  $g_i(X)$  is the gauge coupling constant at the messenger scale  $M_X$ . And 'i' runs over all the gauge groups in the standard model. Except for sleptons all other parameters, scalar squared masses and gaugino masses are set by  $\Lambda$  at the messenger scale where as slepton masses are set by  $\Lambda_L$ . Typically, the soft masses of the singlets  $m_S$  and  $m_N$  are zero at the mediation scale. At the weak scale  $m_N$  does get generated by RGE corrections whereas  $m_S$  remains zero. Using the RGE given in the appendix, the leading log estimate of  $m_N$  at the weak scale is given by

$$m_N^2(M_{\text{SUSY}}) \approx -\frac{1}{16\pi^2} (m_{H_u}^2 + m_L^2 + m_N^2) Y_N^2 \text{Log}\left(\frac{M_{\text{mess}}}{M_{\text{SUSY}}}\right) \quad (11)$$

This generates a large enough positive contribution to  $m_N^2$  at the weak scale as  $m_{H_u}^2$  is negative at the weak scale from the requirement of electroweak symmetry breaking. The question then remains whether with the above boundary conditions it is possible to reproduce either of the conditions  $m_N \gtrsim M_R$  or  $m_L \gtrsim M_R$  to enhance the Higgs mass significantly.

Assuming as before only one right-handed neutrino and one singlet, we find that it is indeed possible to generate a Higgs mass of 125 GeV. We have to choose an appropriate boundary condition for the third generation sleptons such that it is close to the  $M_R$  mass. In the table I we present

$m_h[GeV]$	$y_N$	$M_R[GeV]$	$m_{\tilde{t}_1}[GeV]$	$m_{\tilde{t}_2}[GeV]$	$\Lambda[GeV]$	$\Lambda_L[GeV]$	$m_L[GeV]$	$m_N[GeV]$	$m_S[GeV]$
127.21	0.62	1787	943	1078	$10^5$	$5.2 \cdot 10^5$	1791	808	0
124	0.82	2056	940	1072	$10^5$	$6 \cdot 10^5$	2046	846	0

TABLE I: Parameter space in general gauge mediated supersymmetric inverse seesaw model

two example points which have this characteristic. It is clear that the two example points given in the table corresponds to the case  $m_L \sim M_R$  discussed in the section-2.

#### IV. SUMMARY

Inverse seesaw model has many interesting features and serves as an important alternative to the regular seesaw model. Supersymmetric versions of this model have been studied earlier in the literature. In the present work, we have discussed the detailed anatomy of the one loop corrections to the neutral CP even Higgs boson masses. We show that the corrections can be significant in cases where the soft mass of either the singlet or the doublet sneutrino is comparable or greater than the right-handed neutrino mass (for reasonable values of Dirac coupling). An enhancement of 6-12 GeV or even more can be easily achieved. This removes the requirement of a large stop mixing parameter  $X_t$  (for stop masses less than a TeV) in models where low scale inverse seesaw mechanism is implemented.

An interesting application of this model lies in general gauge mediation where we have shown that implementing inverse seesaw model can enhance the light Higgs mass to the 125 GeV for stops less than a TeV, without resorting to any mechanism to enhance the stop mixing parameter  $X_t$ .

#### Acknowledgments:

SKV is supported by DST Ramanujan Grant SR/S2/2008/RJN-25 of Govt of India. VSM is supported by CSIR fellowship 09/079(2377)/2010-EMR-1. EJC was supported by SRC program of NRF Grant No. 2009-0083526 funded by the Korea government (MSIP) through Korea Neutrino Research Center.

## Appendix A: Appendix

Here we have collected the expressions for  $B_{ij}$  and  $A_{ijk}$ 's which are used in the calculation of one-loop corrected Higgs mass.

$$B_{ij} = \frac{\partial m_{\nu_i}^2}{\partial H_j}$$

$$A_{ijk} = \frac{\partial B_{ij}}{\partial H_k}$$

$$\tilde{B}_{12} = 2 y_N m_D \left( \frac{m_L^2 - m_S^2}{d_2} + \frac{X_N A_N}{d_1} \right); \quad \tilde{B}_{11} = -2 y_N m_D \frac{\mu X_N}{d_1}; \quad \tilde{B}_{22} = 2 y_N m_D - 2 y_N m_D \frac{X_N A_N}{d_1}$$

$$\tilde{B}_{21} = \frac{2 y_N m_D \mu X_N}{d_1}; \quad \tilde{B}_{32} = -\frac{2 y_N m_D M_R^2}{d_2}; \quad \tilde{B}_{31} = 0$$

$$\tilde{A}_{111} = \frac{2 y_N^2 \mu^2}{d_1}; \quad \tilde{A}_{112} = -\frac{A_N}{\mu} \tilde{A}_{111}; \quad \tilde{A}_{122} = 2 y_N^2 \left( 1 + \frac{A_N}{d_1} + \frac{M_R^2}{d_2} \right)$$

$$\tilde{A}_{211} = -\tilde{A}_{111}; \quad \tilde{A}_{212} = \frac{A_N}{\mu} \tilde{A}_{111}; \quad \tilde{A}_{222} = 2 y_N^2 \left( 1 - \frac{A_N}{d_1} \right)$$

$$\tilde{A}_{311} = 0; \quad \tilde{A}_{312} = 0; \quad \tilde{A}_{322} = -2 y_N^2 \frac{M_R^2}{d_2}$$

$$B_{22} = 2 |H_u| y_N^2 + \frac{|H_u|^3 y_N^4}{M_R^2}; \quad B_{32} = 2 |H_u| y_N^2 + \frac{|H_u|^3 y_N^4}{M_R^2}$$

$$A_{222} = 2 y_N^2 + \frac{3 |H_u|^2 y_N^4}{M_R^2}; \quad A_{322} = 2 y_N^2 + \frac{3 |H_u|^2 y_N^4}{M_R^2}$$

where we have suppressed the generation indices.

## Appendix B: RGE equations in SISM

In the last section of the appendix we present the renormalisation group equations for some of the superpotential and soft terms relevant to the analysis of general gauge mediation. To derive the formulae we use the standard formulae available in the literature[33, 34]. The notation we use is  $t = \text{Log}(\frac{\mu}{m_{SUSY}})$ .

$$\frac{dy_i}{dt} = \frac{y_i}{16\pi^2} \gamma_i^{(1)}$$

$$\frac{d\mu}{dt} = \frac{\mu}{16\pi^2} \left[ 3y_t^2 + 3y_b^2 + y_N^2 + y_\tau^2 - 3g_2^2 - \frac{3}{5}g_1^2 \right]$$

$$\frac{d\mu_s}{dt} = 0$$

$$\frac{dM_R}{dt} = \frac{M_R}{16\pi^2} 2y_N^2$$

where

$$\begin{aligned}
\gamma_t^{(1)} &= \left[ y_N^2 + 6y_t^2 + y_b^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2 \right] \\
\gamma_b^{(1)} &= \left[ 6y_b^2 + y_t^2 + y_\tau^2 - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{7}{15}g_1^2 \right] \\
\gamma_\tau^{(1)} &= \left[ y_N^2 + 3y_b^2 + 4y_\tau^2 - 3g_2^2 - \frac{9}{5}g_1^2 \right] \\
\gamma_{y_N}^{(1)} &= \left[ 4y_N^2 + 3y_t^2 + y_\tau^2 - \frac{3}{5}g_1^2 \right] \\
\frac{dm_{H_u}^2}{dt} &= \frac{1}{16\pi^2} \left[ 3x_t + x_N - 6g_2^2 M_2 - \frac{6}{5}g_1^2 M_1^2 + \frac{3}{5}g_1^2 \xi \right] \\
\frac{dm_{H_d}^2}{dt} &= \frac{1}{16\pi^2} \left[ 3x_b + x_\tau - 6g_2^2 M_2 - \frac{6}{5}g_1^2 M_1^2 - \frac{3}{5}g_1^2 \xi \right] \\
\frac{dm_N^2}{dt} &= \frac{1}{16\pi^2} [2x_N] \\
\frac{dm_S^2}{dt} &= 0
\end{aligned} \tag{B1}$$

where

$$\begin{aligned}
x_t &= 2y_t^2 (m_{H_u}^2 + m_{Q_3}^2 + m_{U_3}^2) + 2A_t^2 \\
x_b &= 2y_b^2 (m_{H_d}^2 + m_{Q_3}^2 + m_{d_3}^2) + 2A_b^2 \\
x_\tau &= 2y_\tau^2 (m_{H_d}^2 + m_{L_3}^2 + m_{e_3}^2) + 2A_\tau^2 \\
x_N &= 2y_N^2 (m_{H_u}^2 + m_{L_3}^2 + m_N^2) + 2A_N^2
\end{aligned} \tag{B2}$$

**Appendix C: Approximate sneutrino egenvalues for  $M_R \sim m_L$**

$$\begin{aligned}
m_{\tilde{\nu}_1}^2 &\approx m_L^2 + m_D^2 \left( 1 - \frac{m_L^2}{m_S^2} - \frac{X_N^2}{m_N^2} \right) \\
m_{\tilde{\nu}_2}^2 &\approx m_N^2 + m_L^2 + m_D^2 \left( 1 + \frac{X_N^2}{m_N^2} \right) \\
m_{\tilde{\nu}_3}^2 &\approx m_S^2 + m_L^2 + m_D^2 \frac{m_L^2}{m_S^2} \\
\tilde{B}_{11} &= 2 y_N m_D \frac{\mu X_N}{m_N^2}; \quad \tilde{B}_{21} = -\tilde{B}_{11} \\
\tilde{B}_{12} &= 2 y_N m_D \left( 1 - \frac{m_L^2}{m_S^2} - \frac{X_N A_N}{m_N^2} \right) \\
\tilde{B}_{22} &= 2 y_N m_D \left( 1 + \frac{X_N A_N}{m_N^2} \right) \\
\tilde{B}_{32} &= 2 y_N m_D \frac{m_L^2}{m_S^2} \\
\tilde{A}_{111} &= -\frac{2\mu^2 y_N^2}{m_N^2}; \quad \tilde{A}_{112} = -\frac{A_N}{\mu} \tilde{A}_{111} \\
\tilde{A}_{122} &= 2y_N^2 \left( 1 - \frac{A_N^2}{m_N^2} - \frac{M_R^2}{m_S^2} \right); \quad \tilde{A}_{211} = -\tilde{A}_{111} \\
\tilde{A}_{212} &= \frac{A_N}{\mu} \tilde{A}_{111}; \quad \tilde{A}_{222} = 2y_N^2 \left( 1 + \frac{A_N^2}{m_N^2} \right) \\
\tilde{A}_{322} &= 2y_N^2 \frac{M_R^2}{m_S^2}
\end{aligned} \tag{C1}$$

Approximate formula for the bound on the mass of the lightest Higgs boson is given by

$$m_h^2 \leq M_Z^2 \cos^2 \beta^2 + \Delta \mathcal{M}_{\sqcup 22}^2 \sin^2 \beta^2 + \Delta \mathcal{M}_{\nu 22}^2 \sin^2 \beta^2 \tag{C2}$$

$\Delta \mathcal{M}_{11}^2$  and  $\Delta \mathcal{M}_{12}^2$  contribution is very small, compared to  $\Delta \mathcal{M}_{22}^2$ , can be neglected. To estimate neutrino contribution to Higgs mass we have considered  $\Delta \mathcal{M}_{\nu 22}^2$  in the approximations  $M_R \sim m_L$  and  $A_N=0$ , which is given by

$$\begin{aligned}
\Delta \mathcal{M}_{\nu 22}^2 &= 2k \left( \tilde{L}_1 \tilde{B}_{12}^2 + \tilde{L}_2 \tilde{B}_{22}^2 + \tilde{L}_3 \tilde{B}_{32}^2 + m_{\tilde{\nu}_2}^2 \tilde{A}_{222} (\tilde{L}_2 - 1) + m_{\tilde{\nu}_3}^2 \tilde{A}_{322} (\tilde{L}_3 - 1) \right) \\
&\quad - 4k \left( L_2 B_{22}^2 + L_3 B_{32}^2 + m_{\nu_2}^2 A_{222} (L_2 - 1) + m_{\nu_3}^2 A_{322} (L_3 - 1) \right)
\end{aligned} \tag{C3}$$

From Appendix-A, it is clear that A's and B's corresponding to right-handed neutrino part is are small compared to that of sneutrinos. Thus fermion contribution can be safely neglected (this is not true when  $m_{SUSY} \ll M_R$ ) and C3 becomes

$$\begin{aligned}
\frac{\Delta\mathcal{M}_{\nu 22}}{(2k)} &\approx 4m_D^2 y_N^2 \left[ \tilde{L}_2 + \frac{M_R^4}{m_S^4} L_3 + \frac{(M_R^2 - m_S^2)^2}{m_S^4} \tilde{L}_1 \right] \\
&\quad + 2m_{\tilde{\nu}_1}^2 y_N^2 \left[ \left( \frac{M_R^2}{m_S^2} - 1 \right) (1 - \tilde{L}_1) \right] + 2m_{\tilde{\nu}_2}^2 y_N^2 [\tilde{L}_2 - 1] \\
&\quad + 2m_{\tilde{\nu}_3}^2 y_N^2 \left[ \frac{M_R^2}{m_S^2} (\tilde{L}_3 - 1) \right]
\end{aligned} \tag{C4}$$

Typically all the sneutrino masses are of  $O(10^6)$  (while log factors are of  $O(1)$ ) and can be taken to be equal.

$$\begin{aligned}
\frac{\Delta\mathcal{M}_{\nu 22}}{(2k)} &\approx 4m_D^2 y_N^2 \left[ \tilde{L}_2 + \frac{M_R^4}{m_S^4} \tilde{L}_3 + \frac{(M_R^2 - m_S^2)^2}{m_S^4} \tilde{L}_1 \right] + 2m_{\tilde{\nu}}^2 y_N^2 \left[ \frac{M_R^2}{m_S^2} \frac{\tilde{L}_3}{\tilde{L}_1} \right. \\
&\quad \left. + (-2 + \tilde{L}_1 + \tilde{L}_2) \right]
\end{aligned} \tag{C5}$$

From eq (C5), it is evident that Higgs mass receives large correction from sneutrino masses. As sneutrino masses implicitly depend on  $m_D$ , increase in  $m_D$  increases the Higgs mass.

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